

A comprehensive review of different electric motors for electric vehicles application

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ABSTRACT

Electric vehicles (EVs) offer several advantages over internal combustion engines (ICE), including high energy efficiency, noise reduction, low maintenance, and a wider speed range. This results in lower fuel consumption, reducing dependency on oil imports and enhancing energy security. The motor drive is a critical component of EVs, providing the necessary propulsion force. This paper presents a comprehensive comparison of state-of-the-art motors suitable for EV applications, including DC motors, induction motors (IM), brushless DC motors (BLDC), permanent magnet synchronous motors (PMSM), and switched reluctance motors (SRM). Various design aspects relevant to traction applications, such as cost, reliability, efficiency, torque, fault-tolerance ability, excitation arrangements, and power density are also addressed. The performance of an EV based on the SRM drive is analyzed using MATLAB Simulink, with a special focus on parameters like speed, torque, flux, and state of charge (SOC). The review highlights that SRM drives have significant potential in EVs due to their reliable structure, fault tolerance capability, and magnet-free design. However, their application in EVs is currently limited due to torque ripples, as evident from the simulations. This paper is expected to serve as a foundation for further enhancing the performance of SRM drives for EV applications.

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1. INTRODUCTION

Recently, EVs have gained attention due to their eco-friendly nature and reduced greenhouse gas (GHG) emissions, fuel costs, pollution, and noise. Particularly in developing countries and large cities, the transport sector is a major source of harmful exhaust emissions, including particulate material (PM), nitrous oxides (NOX), carbon monoxide (CO), and sulphur dioxide (SO₂), resulting in various health issues. Sustainable electric mobility is the key to the future for minimizing the environmental impact and accelerating development. A majority of urban planning commissions across the globe have set their sights on transforming their transportation networks to environmentally friendly alternatives by the year 2040 [1]. Electric vehicles (EVs) can be used for vehicle to grid (V2G) and vehicle to house (V2H) services for flexible power transfer [2]. Moreover, they play a supportive role in the utility grid by incorporating renewables such as solar PV and wind generation to effectively manage the increasing power demand. Smart charging within the electric vehicle charging system (EVCS) has several functionalities, including battery recharging, offering reactive power compensation to support the grid, mitigating harmonics, and enabling bidirectional power flow with the grid [3]. The adoption of electric vehicles (EVs) is influenced by various

factors, encompassing both technical and economic aspects such as battery capacity, power consumption, annual mileage, and the size of the locality [4]. The primary concerns in electric vehicle (EV) development include cost, space constraints, flexibility, efficiency, and voltage control. An emerging trend in power electronics for EVs is the implementation of integrated converters [5]. Compared to conventional converters, integrated converters boast higher efficiency, reduced output ripple, and a more compact design [6], [7].

Electric energy serves as the primary power source for electric propulsion in EVs. This rotational energy is applied to the vehicle wheels through an appropriate transmission system, enabling propulsion [8]. Meeting efficiency, power density, and drivetrain cost targets in EVs requires advanced motors. The performance of these motors depends on the vehicle's duty cycle, thermal characteristics, and the cooling mechanism employed. Selecting suitable motors for electric vehicles is crucial, as the driving response heavily relies on the motor drive for traction applications [9]. There are also aspects like owner expectations, vehicle constraints, and power sources. Taking these into account, the motor operating point is not clearly defined. Hence, selection of the most suitable motor for an EV is a challenging task. This paper makes the case for switched reluctance motor (SRM) in EVs due to its compact size, wide speed range, low cost, higher efficiency, and fault tolerance ability [10]. It doesn't employ conductors or permanent magnets on the rotor like permanent magnet synchronous motors (PMSM) and induction motors (IM) do. The widespread adoption of SRMs in powertrain applications has been hindered primarily by two challenges, that's high torque ripple and significant acoustic noise and vibration. The design parameters for motor selection in EVs are high power-to-weight ratio, torque-speed characteristics, reliability, efficiency, controller expense, and overall cost. These topics have been covered in the relevant literature from various aspects. This study aims to provide a comprehensive review of the existing knowledge, presenting the current state-of-the-art in electric vehicle systems. Additionally, it delves into a thorough examination of competing electric motor technologies, analyzing their advantages and disadvantages. This paper demonstrates the effective implementation of the proposed SRM drive for powering an EV and the performance is satisfactory except for torque ripples and resulting radial distortion.

The first section provides an outline of different EV topologies and the parts of the powertrain. The second section provides an overview of the motors and evaluates them based on the main requirements for an EV application. Inferences are made to identify the most suited motor for EVs keeping in with the latest trends and developments. This paper also provides an effective utilization of the proposed SRM drive for driving an EV with simulation and performance analysis.

2. RELATED WORK

2.1. Electric traction system and EV power train architecture

Electric vehicles (EVs) have the option to use electrical energy as the sole power source or combine batteries with internal combustion engines (ICE) for propulsion. Figure 1 illustrates the configuration of an EV traction system, which includes key components such as the power source, electronic controller, motor, transmission system, and on-board battery charger. An auxiliary power supply is also present to provide power for auxiliary systems, such as power steering and temperature control units responsible for regulating the battery temperature [11].

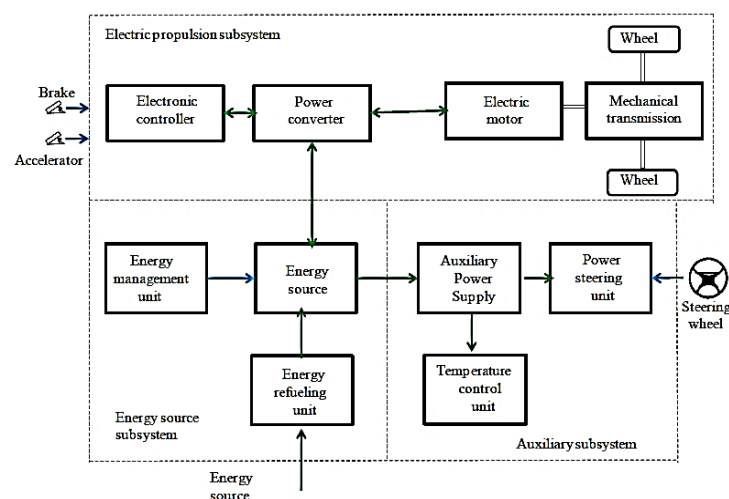


Figure 1. Typical configuration of an EV

The construction of an electric vehicle (EV) offers greater flexibility compared to a conventional internal combustion engine (ICE) vehicle, due to the reduced number of movable components. Instead of the clutch and traditional transmission scheme, EVs employ a simple gear ratio, in addition to a simplified ICE arrangement. Figure 2 illustrates a typical parallel hybrid electric vehicle (HEV). The ICE, the motor, or both may be used to power the propulsion system. The fundamental components of an EV drive include electric motors, batteries, and associated controllers. An integrated motor drive (IMD), involves the structural integration of the motor and the drive as a single unit. This integration leads to a significant increase in power density, reducing the volume by 20-30%, and also reduction of installation and manufacturing expenses by 40-50% [12].

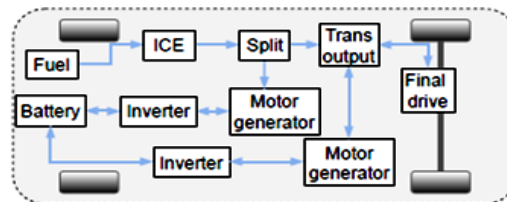


Figure 2. Typical components of an electric vehicle drive

2.1.1. Charging system

Alternating current (AC) charging systems provide an AC supply transformed to DC to recharge the batteries. Fast charging of EVs is made possible via DC charging, which offers more power than AC systems. Table 1 display the AC and DC charging standards recommended by the society of automotive engineers.

Table 1. Charging power levels for EV

AC charging	System voltage (V)	Maximum current (A)	Output power (kW)
Level 1	120 V, Single phase	12	1.08
	120 V, Single phase	16	1.44
Level 2	208 – 240 V, Single phase	16	3.3
	208 – 240 V, Single phase	32	6.6
	208 – 240 V, Single phase	≤ 80	≤ 14.4
Level 3	208/480/600 V	150-400	3
DC charging	Voltage limits (V)	Largest possible current (A)	Output power (kW)
Level 1	200-450	80	36
Level 2	200-450	200	90
Level 3	200-600	400	240

Charging options for electric vehicles (EVs) include off-board and on-board methods, which can be conductive or inductive. These methods allow for unidirectional or bidirectional power transfer, enabling energy flow between the vehicle's battery and the grid. On-board chargers must adhere to weight, space, and cost restrictions, also sufficient charging infrastructure can help lessen the on-board energy storage requirements and charges. To maximize the real power obtained from the utility, EV chargers should operate with a high power factor and low distortion [13]. On-board chargers only provide level 1 power due to their weight and limited space resulting from expensive circuitry. Another category called integrated chargers saves weight, size, and cost by combining the charging with the driving function. Power converters are crucial for the charging mechanism of any battery to enable fast and slow charging as per the requirements [14]. Wireless power transfer (WPT) technique has also become prevalent due to its safety and flexibility in EVs charging and they can also assist in V2G or vehicle to home (V2H) system as described in [15].

2.1.2. Energy storage system (ESS)

The fundamental requirements for a good ESS for an EV are high specific energy for extended range, good specific power for acceleration, rapid charging, prolonged life, low cost, and maintenance. The various ESS is given in the Ragone plot in Figure 3. Lithium-ion batteries are the most prevalent variety and the battery management system (BMS) controls the battery state including the state of charge (SOC), state of health (SOH), and cell capacity to enable a safe and effective functioning. It is also significant to estimate these model parameters in real-time, depending on the current/voltage data measured when the battery is running [16]. Pulse charging techniques with intelligent battery management enable better control of the

parameters to boost the performance [17]. An extended Kalman filter for estimating the SOC was proposed in [18] and this method can compute the useful energy left in the battery for EV applications. Ultra-capacitor (UC) offers high power density, especially with regenerative braking but has low energy density. By combining battery-UC hybrid storage, the drawbacks of each individual system are overcome, resulting in a dependable and reliable energy option. Fuel cells, such as hydrogen fuel cells and flywheels, are other options for storing energy.

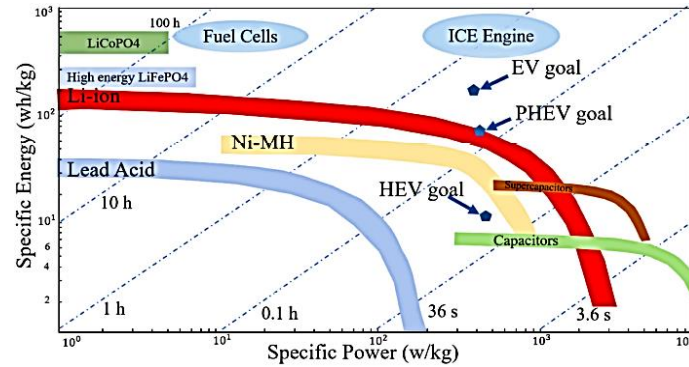


Figure 3. Different energy sources in Ragone plot [19]

2.1.3. Power modulators

Various methods of power conversion are available, as shown in Figure 4. After energy conversion from the AC grid, ESS stores it as DC. It also enables reverse power flow, allowing power to be supplied to the utility during vehicle idling (V2G) or regenerative braking to recharge the batteries. The converter control algorithms should be designed so that each motor operates at maximum efficiency, often between 90% and 95% [20]. There are promising control methodologies, such as neural networks, fuzzy controllers, adaptive neural fuzzy inference systems (ANFIS), and adaptive model reference control, for EV traction. Suppression of electromagnetic interference (EMI) noise is an important design aspect and digital chaotic pulse width modulation (DCPWM) techniques can be used to reduce the EMI during the switching process [21].

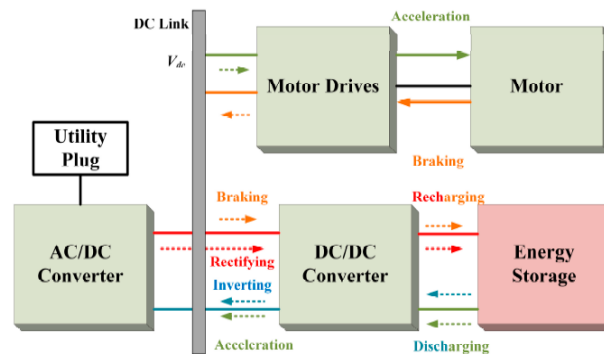


Figure 4. Power modulators in an EV

2.1.4. Methodology for motor selection for electric vehicle application

Different motors exhibit distinct characteristics, underscoring the importance of evaluating motors based on fundamental parameters to identify the most suitable option for an EV. Desired attributes for electric motors include a simple and compact design, excellent specific power, low maintenance cost, and effective control. Depending on the road conditions, EVs would require changing speed, boosting torque on hills, and suddenly applying the brakes. A model load profile is given in Figure 5. This study focuses on conducting a comprehensive multi-criteria comparison of electric motors used in electric traction systems. The objective is to facilitate the selection of the most appropriate motor centered on the recent trends and the

significant factors for EV traction. A comprehensive evaluation of five distinct types of electric motors is conducted taking into account factors like performance, efficiency, reliability, fault tolerance, dynamic response, torque capability, and cost. The recent developments in motor design are also considered like thermal management, controllability, and power density based on the existing literature. The main prerequisite for motors in EVs is [22]:

- High power density and rapid power;
- Very high torque even at low speeds for starting and climbing, and high power at high speeds during cruising;
- Broad speed range, in regions with steady torque and power;
- Good torque response for dynamic operations;
- High efficiency for a wide range of speeds and torques;
- Effective regenerative braking;
- Excellent reliability and dependability under different vehicle operating cases; and
- Economical price.

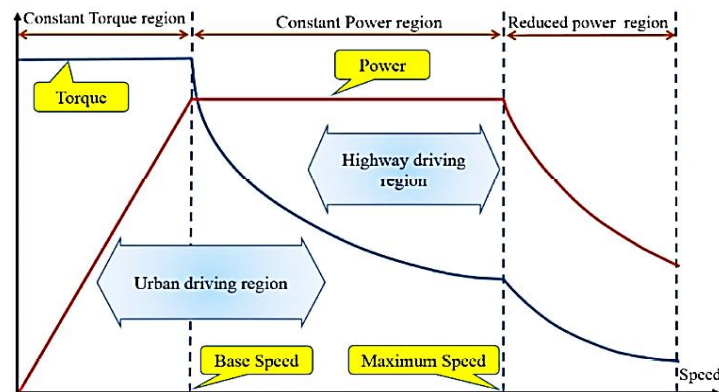


Figure 5. Speed-torque profile of an electric motor for EV application [23]

Additionally, small acoustic noise and torque ripple are vital design aspects. From an industrial and manufacturing aspect, the market acceptance of the motor type is essential [24]. This decides the comparative availability and associated power electronics cost. The factors that govern the motor selection are given in Figure 6. The commonly used motors by EV manufacturers are shown in Figure 7.

DC motors have been commonly used in EVs as their torque-speed profile suits the traction requirement due to their ease of speed control. Mechanical commutators/brushes are heavy, inefficient, unreliable, and require maintenance due to sparking, wear, and tear [25], [26]. Brushless DC (BLDC) motors have lesser maintenance and higher efficiency as they incorporate electronic commutation (inverter and rotor-position sensors) instead of mechanical commutation [27]. They have better-operating characteristics even at higher speeds, making them suitable for EVs, compressors, and pumps. The PMLDC motor's pricey rotor magnet and limited field weakening ability are its drawbacks [28]. Cage induction motors (IM) is extensively employed in EVs for their reliability, ruggedness, less maintenance, and cost [29], [30]. The drawbacks of IMs are large loss, low efficiency, poor power factor, and low inverter-usage factor [31]–[33]. They also have drawbacks such as:

- In order to realize machine-reactive power requirements like field-oriented control, sophisticated excitation setups are necessary;
- The low-speed machine characteristics affect performance;
- Fault in one of the phases has a significant impact on the developed torque; and
- High-cost power converters are required to minimize field speed to allow regenerative operation during braking or deceleration.

Synchronous motors are widely used in EVs, servo applications, and wind turbines due to their higher power density (output power/unit volume). Direct torque control (DTC) using hybrid control methods such as adaptive neuro-fuzzy inference system (ANFIS) controller can further provide rapid and reliable torque, better speed control, and superior performance [34]. These motors have been utilized by numerous automakers, including Nissan, Honda, and Toyota. The price of rare earth magnets like NdFeB is the main barrier [35]. Another flaw is the additional current required to weaken the field, which increases stator losses and affects productivity at high speed. For EV applications, SRM are a viable choice because of their strong

starting torque, extensive speed range, and fault-tolerance capacity [36]. These motors are easy to control, have a simple structure, and good torque-speed characteristics. Some shortcomings include torque ripple, bus current ripple, electromagnetic interference (EMI) noise, and acoustic noise, but their merits outweigh the demerits [37]. They can be employed in light and heavy EV applications [38], [39].

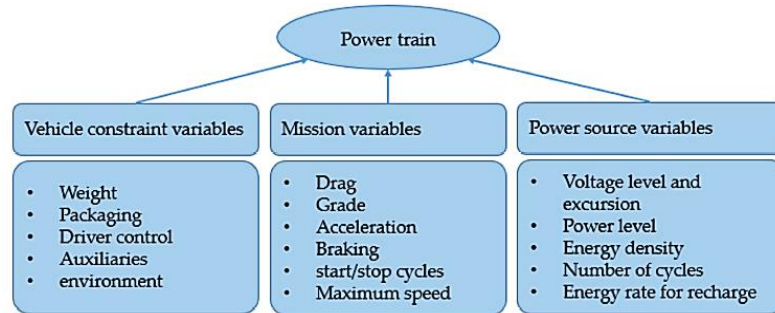


Figure 6. Factors for EV motor selection

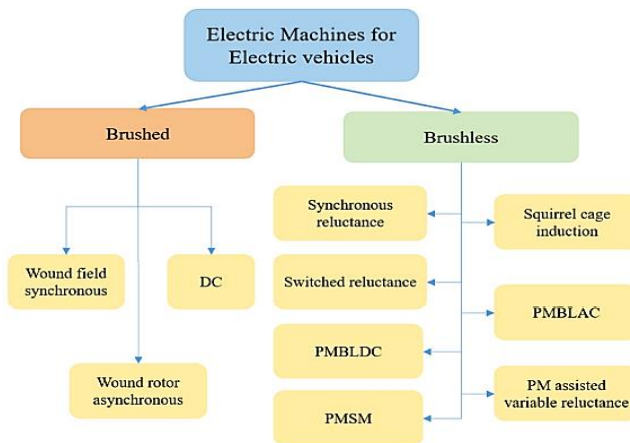


Figure 7. Motors for EV application

2.2. Motor integration and thermal control systems

With their ability to generate high torque and wide constant power speed range, PMSMs are increasingly used for EV systems. This enables them to achieve the desired performance. Numerous leading EVs employ motors constructed with rare earth magnets, particularly neodymium iron boron, which offer excellent torque density, efficiency, and a lightweight and compact structure [40]. As a long-term option, they can be costly, leading to increased material expenses for the motor. These motors are inefficient during usual vehicle operating conditions due to the necessity of field weakening to achieve higher speed operation. Therefore, there is a pressing need for the automotive industry to develop stringent guidelines by conducting a comprehensive life cycle assessment [41]. Removing rare-earth magnets reduces the dependence on this vital component. IMs are no longer feasible solutions because of the rising need for high specific power and power density requirements. Synchronous reluctance machines (SynRMs) are also appealing due to their durability, efficiency, minimal ripple, and control. Still, they have a lower power factor, which affects the converter design and price and limits the constant power-speed range. SRMs and SynRMs have large scope for EVs with better design and research. There are replacements for rare earth motors including a rare-earth free-based PMSM, a ferrite PM (Fe-PM), and PM based SynRM [42]. Thermal management, including temperature, influences the torque/power abilities of a motor. Hence, thermal control is crucial to dissipate the heat generated from the hot spot and other components to maintain the predetermined temperature limits [43]. Efficient integration of motors and converters enables better space and cost management of EVs, compactness, and easy installation with fewer parts. They also reduce electromagnetic interference and voltage overshoots and provide better power density and optimization of manufacturing and installation costs [44]. Table 2 show the commonly used motor-converter integration methods, and it depends on the EV and motor type, and installation cost. Figure 8 depicts the thermal regulation arrangements for cooling the various power train machinery and batteries in EVs.

Table 2. Motor converter integration methods

Configuration	Features
Radial housing	Converter on the top of the motor case
Radial stator	Converter attached on the periphery of the motor stator
Axial endplate	Inverter mounted to the motor end shield
Axial stator	Converter linked to the stator end

Electric-vehicle manufacturers' powertrain and battery thermal management

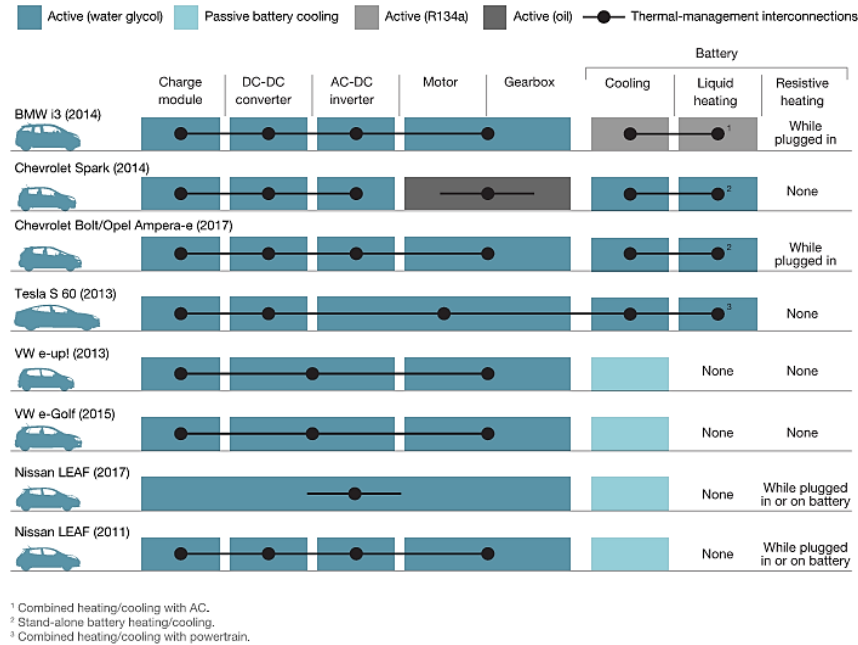


Figure 8. Commonly adapted thermal management systems [45]

3. DESIGN FACTORS FOR ELECTRIC VEHICLES

3.1. Power-to-weight ratio and robustness

The power-to-weight ratio is computed by dividing the motor's peak kW output by its weight in kilograms. Considering various motors with the same power, voltage, and speed ratings, SRM has the highest power-to-weight ratio due to their compact construction, as given in Figure 9 [46]. Robustness is the ability of a motor to carry out a task efficiently despite perturbation or disturbance in its state variables or internal parameters. It can be assessed by applying a disturbance and comparing its performance with that of the original unperturbed system. A resilient motor system will still operate with good efficiency despite the disturbance. SRMs, without permanent magnets and with reduced winding, stand out as more promising candidates for EVs [47]. In addition, they have a good power density, simple construction, and rigid design. Some of the winding types proposed enable the insertion of winding bars into the stator slots for better power densities [48]. Enhancing the winding's thermal conductivity is crucial to increase the power density. Pre-manufactured winding bars give better flexibility in the winding design [49].

3.2. Torque speed characteristics and dynamic response

The ideal torque-speed motor profile for an EV application is shown in Figure 10. The motor applies a constant torque (rated torque) in the constant-torque region throughout the entire speed range up to the rated speed. Once the speed exceeds the rated speed, the torque falls proportionally with speed, and producing constant power (rated power) output. High speeds, where torque falls proportionally to the square of the speed, eventually cause the constant-power region to decrease [50]. The tractive effort characteristic should essentially be constant for an energy source with a fixed power rating. When an EV starts and stops frequently, the motor operates in a constant torque region, whereas at high speeds, it switches to a constant power mode. As seen in Figure 11, a DC series wound motor has a high initial torque, but its speed drops as the torque rises. As illustrated in Figure 11, DC shunt motors display moderate starting torque, and their speed only marginally decreases as torque increases, making them suitable for constant-speed applications.

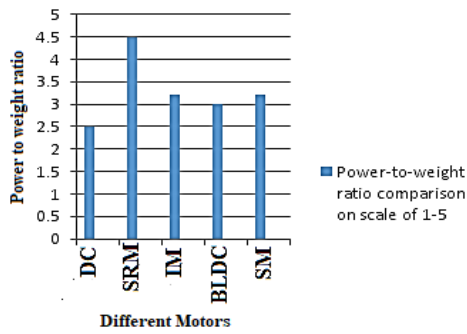


Figure 9. Motor comparison based on power-to-weight ratio

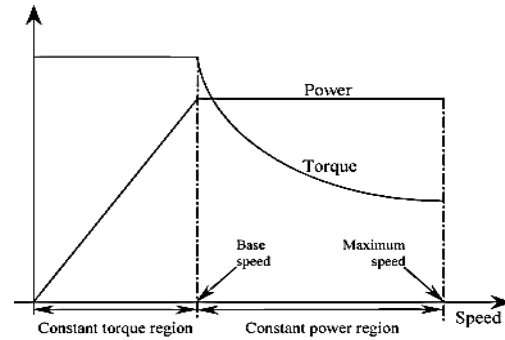


Figure 10. Ideal performance characteristics for a vehicle

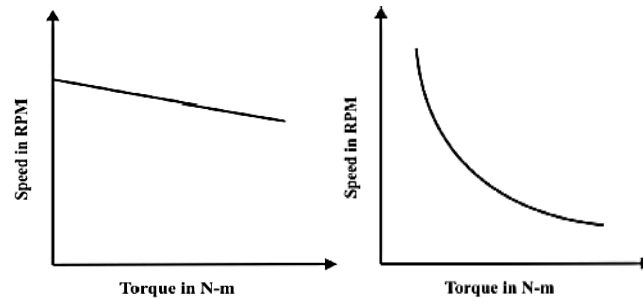


Figure 11. Torque-speed profile of DC series and DC shunt motor

BLDC motors have a drooping torque-speed characteristic as opposed to DC shunt motors [51]. Up to the rated speed, its torque remains constant. When the motor is run at its maximum speed (about 150% of its rated speed), the torque steadily decreases as indicated in Figure 12. The starting torque, pull-out torque, instantaneous speed, and maximum speed of IMs influence their torque-speed characteristics, as depicted in Figure 13. The pull-out torque restricts the speed range at high speeds and restricts its extended constant-power operation [52]. Their torque-speed characteristics change for various values of rotor resistance. At the critical speed, the motor reaches breakdown torque, which is typically twice the synchronous value. Beyond this speed, the motor operates at a maximum current, leading to stalling, which impacts efficiency at high-speed ranges. Consequently, the efficiency of IMs is lower compared to a permanent magnet (PM) motor of similar rating. The pull-out torque varies inversely with total stator and rotor leakage reactance and is independent of rotor resistance. It varies inversely with the square of source frequency and is proportional to the square of stator flux (or voltage). The initial starting torque varies linearly with the square of the voltage source. The initial torque rises as the leakage reactance and the source frequency decrease. The flux reduces with increasing frequency in the flux-weakening zone. The leakage reactance can be reduced by:

- Widen the stator slot apertures;
- Increase the air-gap length to decrease the harmonic leakage flux; and
- Use wide, open rotor slots.

Synchronous motors (SM) are employed in vehicles when constant speed is necessary. Due to permanent magnets, PMSMs have a limited field weakening ability, resulting in a narrow constant-power domain. As depicted in Figure 14, the converter's conduction angle needs to be controlled for functioning above the base speed. Multi-level inverters as proposed in [53] can be utilised to increase efficiency and speed response and extend the operating range.

For an SRM, the rotor is the smallest among all machines, possessing low moment of inertia, which helps the motor, accelerate at a significant rate. Torque above base speed is regulated by modifying the phase turn-on and turn-off angles, while for below base speed, it is regulated by pulse width modulation (PWM) of current. SRMs are typically used in the discontinuous current operation. The PWM of phase currents in the constant torque domain generates the necessary torque. The maximum torque ability depends on:

- Highest current permitted from the converter;
- Rate of current increase after a phase commutation;
- Magnetic circuit saturation level; and
- Permitted temperature increase.

It is imperative to advance the commutation angle for operating above rated speed in the constant power area for a limited inverter voltage. During motoring, turn-on angle determines the peak current, whereas, during generation, turn-on and turn-off angles both have an impact on the peak current. The SRM operational characteristics are suitable for EVs. They can operate in the constant power range, up to 4–6 times the base speed. This is realized by advancing the excitation phase until there is an overlap between consecutive phase currents. Torque-speed profile of an SRM is depicted in Figure 15.

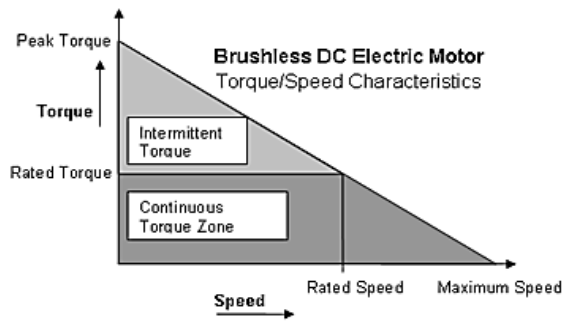


Figure 12. Torque-speed profile of a BLDC motor

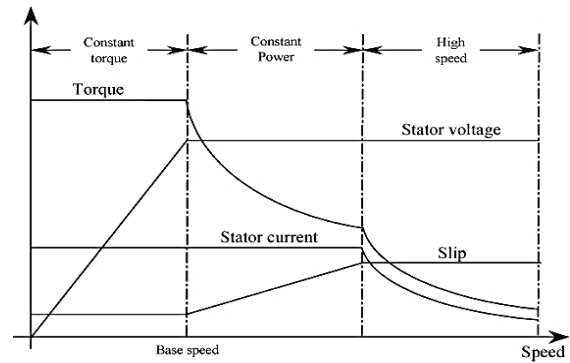


Figure 13. Torque-speed characteristics of a three-phase induction motor

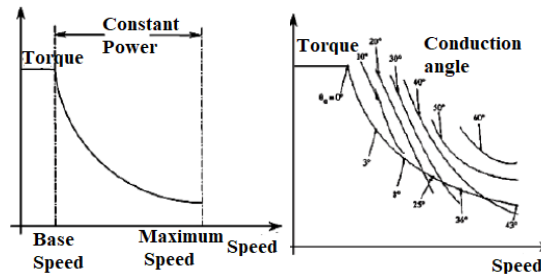


Figure 14. Torque-speed characteristics of a synchronous motor

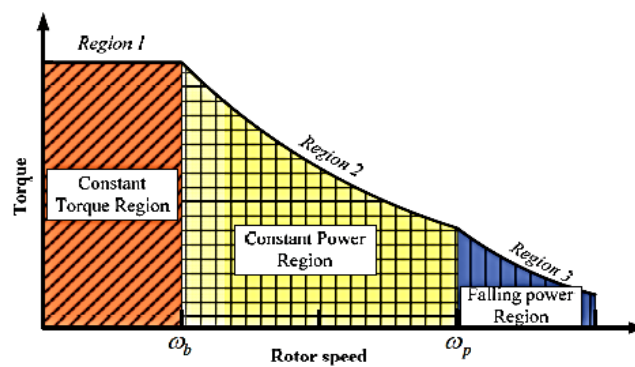


Figure 15. Torque-speed characteristics of an SRM

3.3. Efficiency

The input electrical energy is lost due to windage losses and copper losses. Efficiency is the ratio between shaft mechanical output and power input. Electric motors usually have the highest efficiency at their rated output. For an EV, motors need to operate at various loads. Hence, efficiency at peak load and at other loads should be considered for an EV application [54]. The motor efficiencies are given in Table 3. The presence of concentric windings in SRM also reduces the end-turn build-up, leading to decreased inactive

material and lower resistance and copper losses compared to machines employing a distributed winding structure. The stator serves as the main source of heat generation, making cooling simpler since it is more accessible than the rotor. In comparison to the stator, the rotor losses are significantly smaller. SRM has better operational performance owing to its better torque-speed characteristics, speed range, power density, and high torque and speed capability. The efficiency could still be improved by controlling the torque ripple and noise level.

Table 3. The performance of different motors

Motor	Peak efficiency (%)	Efficiency at 10% load (%)
DC motor	80-85	75-80
BLDC motor	85-90	70-80
Induction motor	80-90	80-90
Synchronous motor	>90	80-85
Switched Reluctance Motor	>90	>90

3.4. Torque ripple and noise level

Torque ripple leads to noise and vibration, affecting stability and riding comfort. The current ripple can also reflect in the source supplying the converter and motor. This also impacts the battery lifecycle. The ripple phenomenon is more predominant in SRM motors. Their applicability for EVs has been undermined due to lower torque density, higher torque pulsation or ripples, and acoustic noise. It is essential to reduce these torque ripples with suitable control techniques using current regulation techniques such as pre-computed current profiling [55]. The converter-motor integration also causes vibration. The electronic converter boards are fragile and more sensitive to vibrations. There is a need to devise techniques to solve these problems to optimize the drive.

3.5. Cost of controllers

Motor controllers help regulate the speed and other parameters of the drive system of an EV. The controller and converter decide the overall drive performance, efficiency, and ease of controllability [56]. The typical controller cost for motors with similar voltage and power ratings is given in Figure 16. The unipolar drive of the reluctance motor enables the converter to require fewer switching devices in comparison to the conventional inverter. From the comparison, it is clear that the SRM motor has an optimum cost and also offers more benefits.

3.6. Motor expense

One of the major challenges for EV manufacturers is to design and provide an efficient and affordable EV. The cost of various motors for similar voltage and output power ratings are given in Figure 17. The cost for SRM is low because of the absence of permanent magnets and windings and due to their compact structure [57]. Windings are located solely on the stator, while the rotor remains free of windings or magnets, resulting in its material savings. Compared to distributed windings found in other motors, concentrically arranged windings in SRM around the poles result in better manufacturing efficiency.

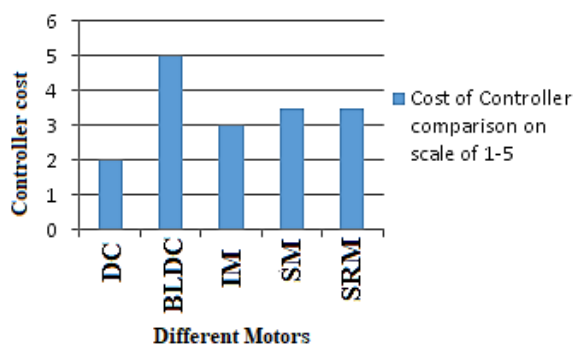


Figure 16. Typical controller cost for electric motors

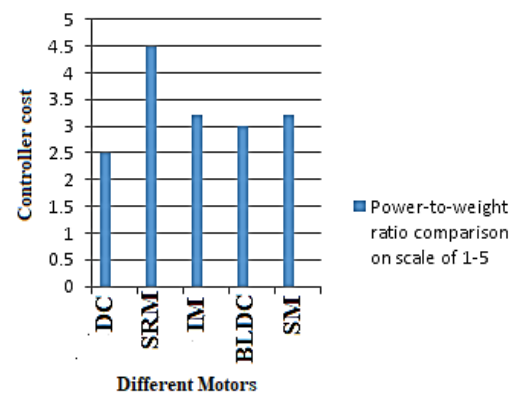


Figure 17. Cost comparison for electric motors

3.7. Fault tolerance capability and overload capacity

Overloading occurs when the winding current exceeds the maximum safe and effective handling capacity of the windings. This can be caused by excessive voltage supply, short circuits, or low voltage supply. The extended use, environmental impact, operational malfunction, and faulty manufacturing during the drive system's operation increase the likelihood of failure, which can affect vehicle safety. Therefore, there is a need for fault control methods in vehicles to ensure consistent and rapid failure detection. Among the motors, SRM has the highest fault tolerance ability due to its phase-independent characteristics including magnetic independence of the phases [58]. The SRM windings are electrically isolated from each other, exhibiting minimal mutual coupling. This unique feature ensures that an electrical fault in one phase typically does not impact other phases.

3.8. Lifetime and reliability

Motor aging depends on environmental, thermal, electrical, and mechanical aspects. The mechanical factors include fatigue, and stress of the motor bearings like damaged rotor bars in induction motors. Electrical issues involve high-bearing currents, overvoltage, and stresses, especially on the insulation and motor coils. Environmental aspects include humidity, external vibration, and temperature. Since SRM eliminates permanent magnets, it is not prone to aging and has a better life and lower cost compared to other motors [59]. SRM has better reliability due to its inherent fault tolerance capability, low maintenance due to compact construction, and lesser components. The induced electromotive force (EMF) depends on the phase current. Therefore, when the winding has no current flowing through it, the induced EMF is zero, making it incapable of sustaining a phase winding fault if the input current is interrupted. This sets it apart from other machines, which can experience faults even without current. This unique characteristic of the SRM contributes to its higher reliability compared to other electrical machines. The SRM allows the liberty to select any number of phases, which contributes to its high reliability. The electrical independence of the phases assures that operation will continue even if one or more phases fail while in use.

4. RESULTS AND DISCUSSION

It is clear that SRM have the most desirable characteristics for EVs based on the parameters discussed. Table 4 shows the comparison of various motors for EV application. Induction motors are widely used in Evs due to their reliability, ruggedness, and low maintenance. There are issues including losses, low efficiency and power factor, and low inverter usage factor in IM drives. PMSMs are strong competitors to IM in Evs. Their advantages include lesser heating, higher power density, and efficiency. PMSMs have demagnetization issues due to armature reactions. They use permanent magnets, leading to high costs, aging, and poor stability. Limited reserves and the environmental impact of extraction, mining, and refining rare earth resources restrict its use in Evs. Permanent magnets are susceptible to extreme temperatures, affecting performance in harsh automotive environments. SRMs hold great promise in addressing the growing demand for cost-effective, high-performance motors while ensuring more reliable and secure supply chain. The current motors heavily bank on on rare earth metals for their permanent magnets that account for only a minor fraction of the global metal production. China is the largest producer of rare earth metals, therefore it has enormous influence over both their price and availability. SRMs rely on easily available, more widely distributed materials like copper and steel rather than permanent magnets.

Switched reluctance motor (SRM) in EV/HEV applications has benefits over other motors, like simple control, rugged construction, superior fault tolerance ability, and superb torque-speed profile. They are apt in applications requiring constant power over a wide operating region. They have high torque per ampere and faster dynamic response with simple and robust power switching circuits, making them apt for high-speed, temperature-sensitive, and safety-critical applications. This saliency also presents a significant challenge in the form of electromagnetic interference, torque ripple, and noise, limiting its applications for Evs. The electromagnetic torque is dependent on both the excitation current and the angle between the poles of the stator and rotor. Phase commutation produces a pulsating waveform for the torque profile by combining the torque from the incoming and outgoing phases. Torque ripple minimization is one of the significant factors for SRM design, especially for traction drive applications. So, to extend its applications in the electric vehicle industry, it is essential to reduce these torque ripples by suitable control techniques. The vibrations affect the gearbox, which experiences gear chatter and vibrations. This reduces their life and durability. The ripples can excite vehicle components. Torque ripple creates a rotational torque that has a tangential element going outward. The shaft resonances excite the structures, resulting in vibrations. Resonant vibrations affect the gearbox, creating noise and vibration, thereby affecting the overall efficiency. Minimizing torque ripple and radial vibration by machine design includes optimizing machine parameters like pole shape, reference current, turn-on, and turn-off angles, air gap, core, winding arrangement, and

geometry modifications. But these methods increase the effective air gap reducing the peak torque. These techniques limit the operating range, and the rotor position estimation should be accurate for good results. Hence, developing a suitable control strategy to minimize the ripples can increase the torque per ampere to enable faster response for operation in applications like Evs. These include average torque control (ATC), direct torque control (DTC), and current profiling, torque sharing function (TSF), current chopping control (CCC), and machine learning algorithms that are a subject for future research.

Table 4. Comparison of motors for EV application

Parameters	Brushed DC motor	Induction motor	PMBLC motor	PMSM	SRM
Commutation	Brushed	Not applicable	Electronic	Electronic	Electronic
Torque speed characteristics	Moderately flat	Non-linear	Flat	Flat	Most desirable for EV
Output power to torque ratio	Low	Medium	High	High	High
Efficiency	Low	Medium	Medium	High	Very High
Speed range	Low	Medium	Medium	High	High
Control	Simple and low cost	Simple and low cost	Complex and expensive	Complex and expensive	Simple and low cost
Overall cost	Low	Low	High	High	Low
Maintenance	High	Occasionally required	Low	Low	Low
Noise	High	Medium	Low	Low	High
Torque ripple	Low	Low	Low	Low	High
Dynamic response	Low	Medium	Medium	High	High
Life	Low	High	Moderate	High	Very High
Fault tolerance ability	Low	Medium	Low	High	Very High

5. SRM DRIVE BASED ELECTRIC VEHICLE

SRMs are known for their outstanding fault tolerance, making them highly reliable in Evs. In contrast, other motors are prone to malfunctioning during faults when compared to SRMs [60]. The SRM drive has the motor, driver circuitry, position sensor, speed, and current controllers, as depicted in Figure 18. Stator windings are energized using an asymmetric bridge converter. The hall effect sensors estimate the rotor position and the shaft encoder encodes the position to control the converter switching to energize various phases sequentially. The proportional integral (PI) controller monitors the speed, and the current is limited within reference values by the hysteresis current controller. Depending on their application, several controllers, including PI controllers, fuzzy, and neural, are used in SRM drives to govern their parameters, including torque, speed, and power output. Other converters, such as integrated battery chargers, C-dump, bifilar, miller converters, and resonant converters, can also be used alongside the controllers for winding excitation and commutation. The converter type affects factors such as the number of switches, price, size of the drive, effectiveness, power quality, and torque ripple.

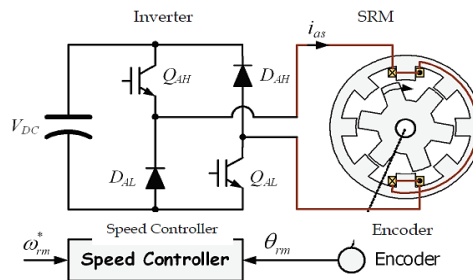


Figure 18. SRM drive with asymmetric converter

5.1. Modeling of electric vehicle dynamics

The dynamics of an EV are simulated by calculating the cumulative tractive forces acting on it to propel the vehicle. It can be represented as:

- Rolling resistance force, $F_r = \mu_r m g$, where g is the acceleration due to gravity, μ_r is the rolling resistance coefficient and m is the vehicle mass;
- Aerodynamic drag is expressed as $F_w = 0.5 \rho A_f C_d V^2$, where ρ is the air density, A_f is the vehicle frontal area, V is the vehicle speed, and C_d is the drag coefficient;

- The grading resistance or force required to climb a hill or slope, $F_g = m.g.\sin\alpha$, where α is the slopes inclination or road angle;
- Linear acceleration force, where $F_{la} = m.a$, where a is the acceleration; and
- Angular acceleration force is given by $F_a = I \cdot G_{ratio} \cdot a / (\eta_g \cdot r^2)$ where r is the tire radius, I is the motor's moment of inertia, G_{ratio} is the transmission gear ratio and η_g is the gear efficiency. Tables 5 and 6 list the various simulation parameters for the SRM-based EV.

Table 5. Modeling parameters for the EV dynamics

Electric vehicle model parameter	Values	Electric vehicle model parameter	Values
Mass of the vehicle (m) (kg)	950	Rolling resistance coefficient (μ_r)	0.005
Drag coefficient (C_d)	0.6	Transmission gear efficiency (η_g)	0.93
Mass density of air (ρ) (kg/m ³)	1.2	Transmission gear ratio (G_{ratio})	16
Payload (kg)	700	Acceleration due to gravity (g) (m/s ²)	9.8
Height (h) (mm)	1300	Regenerative braking factor (R_g)	0.4
Weight (w) (mm)	1500	Vehicle inertia (kg.m ²)	6
Vehicle frontal area (A_f) (m ²)	1.6		

Table 6. Design ratings for the SRM

Parameter	Value	Parameter	Value
Switched reluctance motor (SRM)	No. of stator pole - 10 No. of rotor pole - 8 10/8 five-phase SRM	Stator phase voltage	240V
Stator pole arc	32°	Stator inductance (H)	960
Rotor pole arc	45°	Rated power	10 kW
Aligned inductance (H)	0.02	Reference speed	1500 rpm
Unaligned inductance (H)	0.0006	Reference or maximum current	400 A
Maximum flux linkage (Wb)	0.5	Hysteresis band limits	+/-10 A
Inertia (kg.m ²)	8.9e-3	Stator resistance	0.05 ohm
Friction (Nms)	0.005		

The SRM drive is used for EV application in MATLAB to assess the performance. The SRM can be operated in either maximum torque or maximum efficiency modes based on the road conditions. The simulation is given in Figure 19 and the vehicle model is depicted in Figure 20. The simulations are run, using 1500 rpm as the reference speed and 1.2 seconds as the simulation run time. The development of the SRM drive must be based on application-specific control strategies. The simulation model integrates the essential dynamics of the SRM. As EVs are generally complex systems, performance analysis is critical to improving the design and choosing the components and controllers for actual hardware development.

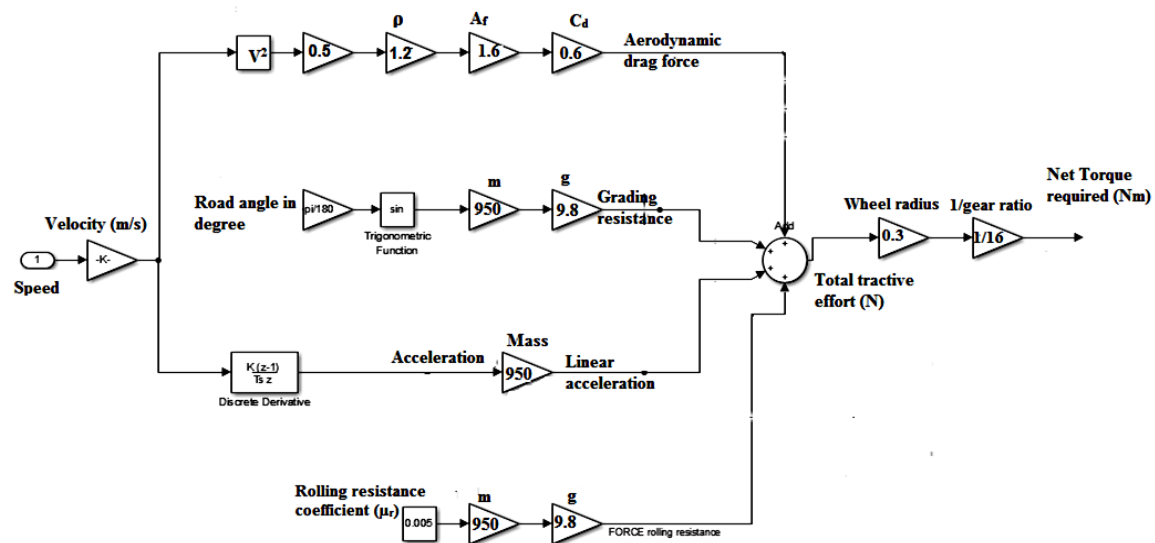


Figure 19. Vehicle model

Dynamic modelling and simulation of the motor are crucial for inner control loop design, drive analysis and future development. For maximum efficiency and optimal operation, electric vehicle drives need to have a high torque/ampere ratio, a low torque ripple, and a broad speed range. This model can be tested with a specific driving cycle to analyze the driving patterns, road conditions, and vehicle emissions. The information can be collected for further reference using a driving cycle tracking device (DC-TRAD) implemented using internet-of-things (IoT) as given in [61]. The torque contributed by each phase is added to deliver the overall torque in Figure 21. The output torque waveform has ripples with a value of 1.6, as shown in the waveform. SRM will have extensive applications in EVs, industrial and domestic drives, servo drives, and aircraft applications once their main shortcomings of torque ripples and noise are overcome. Thus, phase voltage is the control parameter and instantaneous torque is the controlling parameter. The ratio of the difference between the maximum and minimum torque to the average torque is used to calculate torque ripple coefficient. In Figure 22, the speed response attains a steady state within a few seconds, with a reference speed of 1,500 RPM. The battery voltage is given in Figure 23 and battery SOC decreases during the course of EV operation as shown in Figure 24.

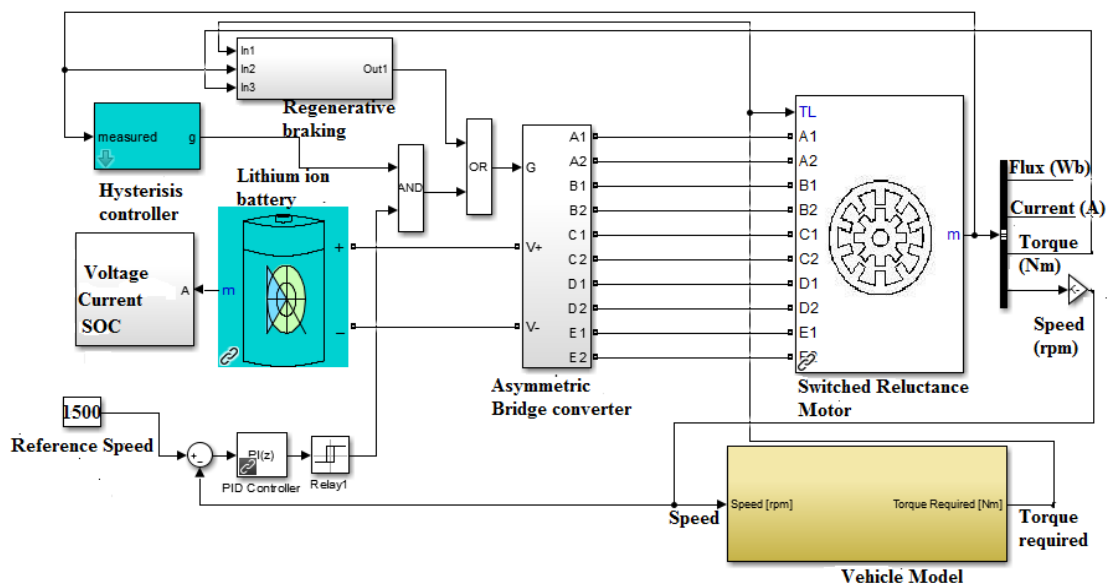


Figure 20. SRM drive based EV model

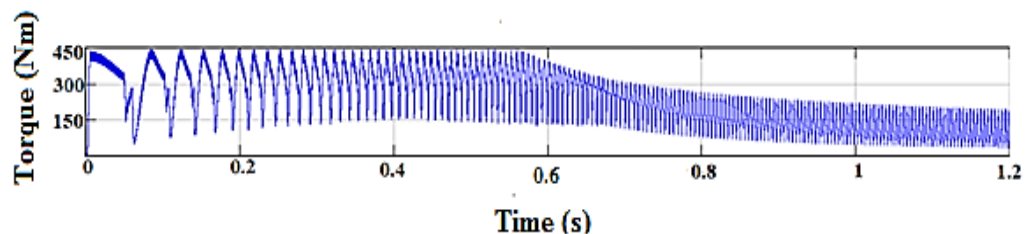


Figure 21. Torque characteristics

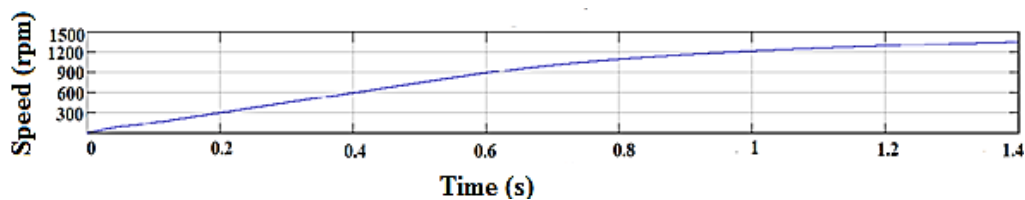


Figure 22. Speed profile

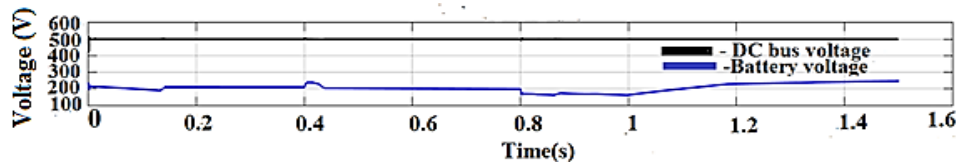


Figure 23. Battery voltage

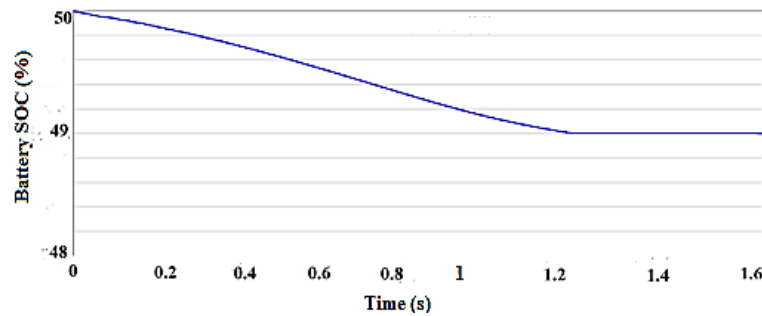


Figure 24. Battery SOC

6. CONCLUSION

EVs have garnered significance due to their potential to minimize the fuel consumption and carbon-dioxide emissions. The operational traits, design aspects, and control necessities for various motors for EV propulsion systems have been studied. Special prominence has been given to SRM as they have better advantages including torque density, and fault tolerance. The commonly used electric motors for EV applications are compared based on design factors such as power-to-weight ratio, torque-speed profile, controller, and motor price. As an application, the SRM drive based EV was simulated and the results indicate good performance. However, the radial noise and torque ripple as depicted in the results must be limited without impacting torque density and performance. The torque ripple can be reduced either through magnetic circuit design during the motor design stage or by implementing torque control techniques. DC motors have ease of control and good torque at low speeds but have extra maintenance costs, bulky size, and lesser efficiency. Although BLDC motors have a good power-to-weight ratio, they require extensive maintenance and expensive controllers. Three-phase IMs have good efficiency and along with BLDC motors, they are commonly used by EVs. Synchronous motors are more effective at slower speeds, have better battery utilization, and driving range. Switched reluctance motors can be a good substitute for IM and BLDC motors due to their overall lower cost, high efficiency at peak load, robustness, and fault tolerance. The SRM drive must be designed by optimizing the topology and control techniques instead of modifying the stator and rotor assemblies to reduce production difficulty and cost. This paper provides a base for further performance enhancements in SRM drives for EV applications. Additionally, it is important to highlight that the obtained model could be helpful for performance evaluation and future development.

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